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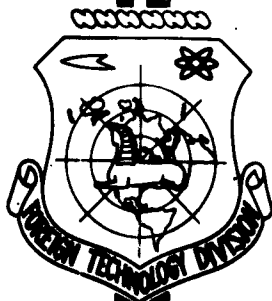
TRANSLATION

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WITH CONSIDERATION OF CHEMICAL NONEQUILIBRIUM

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Heat Transfer in a Laminary Boundary Layer on a Plate with Consideration of Chemical Nonequilibrium

by

V. P. Stulev

Described are results of calculating the field of flow and heat transfer in a boundary layer on a flat plate by the method, described in [1]. Obtained were approximate formulas, representing the effect of variability of physical parameters on the magnitude of thermal flow on the wall.

Par. 1. Equilibrium Flow. Heat transfer on a wall in a boundary layer of reacting atomic-molecular mixture depends upon the change in physical parameters $\mu\rho$ (product of viscosity and density), Prandtl number P and Lewis number L across the boundary layer. Calculation of the thermal flow on the wall in case of equilibrium dissociation is connected with the solution of a complex nonlinear system of ordinary differential equations.

The formulas given below allow to make an approximate calculation of the effect of variability of physical parameters on the thermal stream on the wall provided these parameters change slightly in the boundary layer.

The expression for the thermal flow on the wall with consideration of binary diffusion has the form of

$$q_w = \lambda \frac{\partial T}{\partial y} + \rho D (h^{(w)} - h^{(u)}) \frac{\partial \alpha}{\partial y} \quad (1.1)$$

Changing over to dimensionless variables, we will present q_w through a dimensionless heat exchange factor [2]

$$q_w = \frac{N}{\sqrt{R}} \sqrt{\mu_w \rho_w \frac{u_\infty}{s}} \frac{h_\infty (H_\infty - H_w)}{P_w} \quad (1.2)$$

$$\frac{N}{\sqrt{R}} = \frac{1}{H_\infty - H_w} \left[\frac{\partial h}{\partial \eta} + (h^{(w)} - h^{(u)}) (L - 1) \frac{\partial \alpha}{\partial \eta} \right] \quad (1.3)$$

Here N - Nusselt number, R - Reynolds number, H - total enthalpy, referred to h_∞ .

Solutions for h and α were obtained in form of linear analyses by small parameters ξ_i , characterizing the variability of physical parameters and the degree of nonequilibrium. Taking this under consideration, we will present the ratio N/\sqrt{R} in following forms:

$$\frac{N}{\sqrt{R}} = \frac{N}{\sqrt{R}} \left|_0 \left(1 + \sum_{i=1}^4 \Delta_i \right) \right. \quad (1.4)$$

Here

$$\frac{N}{\sqrt{R}} \Big|_0 = \frac{h_{\infty}}{H_{\infty} - H_w} \quad \Delta_i = \frac{a_i h_{iw}}{h_{\infty}} \quad (i = 1, 2)$$

$$\Delta_3 = \frac{[a_3 h_{\infty} + (h^{(1)} - h^{(2)})(L-1)a_3]_w}{h_{\infty}}, \quad \Delta_4 = 0$$

(1.4a)

The values Δ_i represent the relative effect of variability of physical parameters on the heat flow on the wall. In first approximation the nonequilibrium in a gas particle does not affect heat transfer (provided, the concentration of atoms on the wall is equal to its equilibrium value at wall temperature).

The derivatives h'_{iw} are found from solving the system of first approximation for enthalpy. On the basis of numerical calculations were obtained expressions for these derivative through nondimensional parameters of zero approximation ($h_{\infty}, P^0, K = u_{\infty}^2/h_{\infty}$) and values, characterizing the change in μ_0, P, L numbers across the boundary layer. As characteristic values μ_0 and P were selected magnitudes of these values on the wall. Formulas, determining the effect of variability μ_0 and P on the dimensionless heat exchange factor on the wall, will be written as follows

$$\Delta_1 = \frac{0.3(\mu_{\infty} P_{\infty} / \mu_w P_w - 1)}{1 - h_{\infty} + 1/2 K \sqrt{P^0}}, \quad \Delta_2 = - \frac{0.1(P_{\infty} / P^0 - 1)}{h_{\infty}(1 - h_{\infty} + 1/2 K \sqrt{P^0})} \quad (1.5)$$

The effect of the L number on heat transfer is expressed as follows:

$$\Delta_3 = \sqrt{P^0} \frac{h^*}{H_{\infty}} a_{\infty} (L_w - 1) + \frac{0.1(L_{\infty} - L_w)}{h_{\infty}(1 - h_{\infty} + 1/2 K \sqrt{P^0})} \quad (1.6)$$

The first addend gives here an addition to the heat flow for the case, when $L = L_w \neq 1$. This case was developed by [2].

For small $L_w - 1$ formula from [2] can be presented in form of

$$\Delta_3 = 0.52 \frac{h^*}{H_{\infty}} a_{\infty} (L_w - 1) \quad (1.7)$$

In this way, for $P^0 = 0.6 - 0.7$ the first addend (1.6) offers a value by 30-40% higher, than formula (1.7).

The second addend (1.6) is structurally analogous to (1.5); it takes into consideration the effect of change in L number from the value L_0 across the boundary layer.

Calculations were made for two gases (oxygen and nitrogen). The conditions on the wall and in the oncoming flow changed in the following boundaries:

See attached page 3a for 1.7a

Condition (4), i.e. the temperature range, was selected so, that in the range of pressures, according to condition (1), the gas in the stream was everywhere partially dissociated.

(5) Conditions (2) and (4) assure the following boundaries for K :

$$0.1 < K < 10 \quad (1.7b)$$

For ranges of variables (1)-(5) formulas (1.5) - (1.6) represent satisfactory approximations of mathematical calculation results. For a majority of variants the discrepancy does not exceed 10-20%. It must be remembered, that the errors of the approximation method of solving the nonlinear system of equations [1] have the very same order. In case when temperature distribution within the boundary layer has a maximum, in formula (1.5) - (1.6) instead of μ_0 , P.L per infinity should be taken the values of these magnitudes at maximum temperature.

The first one of the formulas (1.5) is in satisfactory agreement with the result obtained by [2] for cases, when the fractional denominator does not exceed unity, which corresponds to small velocities of oncoming flow.

The finding of more accurate values of heat flow on the wall with consideration of variability of physical parameters, is limited by the fact, that the transfer coefficients, included in these parameters, are known as functions of temperature and concentration only very approximately. An analysis of this problem is given in [3].

According to [4] the P number for reacting atomic-molecular mixture changes very

пах:
 (1) $0.1 < p < 1$ (атм)
 (2) $10^3 \text{ см/сек} < u_{\infty} < 10^4 \text{ см/сек}$
 (3) $0.15 < h_{\infty} < 1$
 (4) $2800^\circ < T_{\infty} < 3500^\circ$, $3000^\circ < T_{\infty} < 4500^\circ$
 $5300^\circ < T_{\infty} < 6500^\circ$, $6300^\circ < T_{\infty} < 8000^\circ$

(17a)
 для O_2
 для N_2

slightly with the change in temperature and concentration in broad limits.

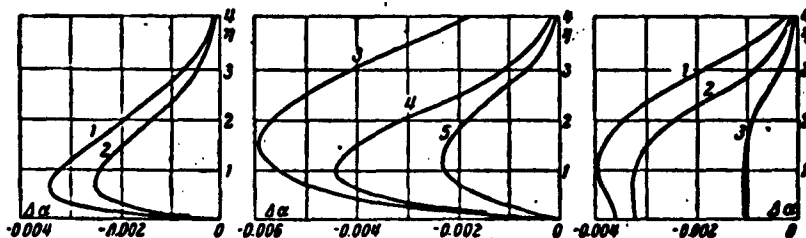


Fig. 2.3

From the second formula is evident (1.5) that the correction to the heat flow is significant. According to calculation data, for the selected dependences of P number upon temperature this correction does not exceed 3-5%.

The effect of L number on the heat flow with consideration of its variability across the boundary layer reaches 20-30%. Of self-sustained interest is a more accurate study the enthalpy and heat transfer profile in the boundary layer with variable number L at simplifying assumptions; $\mu_p = \text{const}$, $P = \text{const}$, equilibrium dissociation. Formula (1.6) can be considered as a method of approximate evaluation of the influence of the L number on heat transfer.

Par. 2. Nonequilibrium Flow. The nonequilibrium field was considered in accordance with formulas from [1]. The concentration of atoms on the wall was accepted as equaling its equilibrium value at wall temperature, so that the deviation from equilibrium appeared on account of particle deceleration in the boundary layer and diffusion of atoms, due to concentration gradients. It was discovered, that everywhere in the boundary layer with exception of the narrow zone at the wall (for a sufficiently low degree of dissociation on the wall) there is a lag in dissociation. Examples of distributing the nonequilibrium share of atom concentration in the boundary layer are shown in fig. 1 and 2. Conditions on the wall and in oncoming flow are listed in table 1. In last column is given the scale by the axis of the abscissas.

Table 1:

1) Curve	2) Gas	3) P, atm	4) $u_\infty \frac{\text{cm}}{\text{cmK}}$	5) $T_\infty^\circ \text{K}$	6) $T_w^\circ \text{K}$	7) Scale
1	2	3	4	5	6	7
1	O_2	0.1	$5 \cdot 10^5$	3500°	3200°	1:1
2	O_2	1	$3 \cdot 10^5$	3700°	3200°	1:10
3	N_2	0.1	10^5	6900°	6000°	1:10
4	N_2	0.1	$5 \cdot 10^5$	6900°	6000°	1:1
5	N_2	0.1	10^5	6900°	6000°	1:10

Under the zone of relaxation for dissociation in boundary layer we will understand such a length, on which maximum deviation from equilibrium dies out, e.g., up to 5%. The dependence of relaxation zone length l_p upon outer conditions can be approximately presented in following form, obtained on the basis of calculating a series of variants:

$$l_p = c p^{-1/2} u_\infty^{-1/2} \quad (2.1)$$

For the range of temperatures mentioned in par.1, the dependence l_p upon wall temperature and oncoming flow may be disregarded.

The linearization method to find the nonequilibrium share in the boundary layer places a restriction on the range of concentrations and, consequently, on the range of temperatures. The method offers satisfactory results at a condition when $0.1 \leq \alpha \leq 0.9$ everywhere in the flow. The inequality is connected with the fact that for $\alpha \leq 0.1$ and $\alpha \geq 0.9$ the dependence $\alpha = \alpha_0(T)$ has essentially a nonlinear character. The profile α_0 acquires greater curvature and the last formula (1.20) of [1] gives unnaturally greater values of the nonequilibrium share of atoms.

Assuming that a catalytic wall assures constant concentration, not equal to its equilibrium value at wall temperature, i.e. $\alpha_w \neq \alpha_0(T_w)$. The heat flow in this case on the wall differs from its value for equilibrium dissociation by a magnitude

$$\Delta h = \frac{h_{\text{eq}} - h_w}{1 - h_{\text{eq}} + 1/2 K \sqrt{P}} \quad (h_{\text{eq}} = h(T_w, \alpha_0(T_w)), h_w = h(T_w, \alpha_w)) \quad (2.2)$$

If $\alpha_w < \alpha_0(T_w)$ (especially, $\alpha_w = 0$ - total recombination) then $\Delta h > 0$, i.e. heat flow increases.

As already mentioned, to calculate the effect of nonequilibrium in the gas molecule

(particle) it is necessary to calculate the second approximation by ϵ_i . It is apparent, that the nonequilibrium in the gas particle has a very insignificant effect on the magnitude of the thermal flow.

Par.3. Nonequilibrium Field in the Problem of a Chemically Insulated Thermometer. The approximate dependence of the length of the relaxation zone upon pressure and rate of oncoming flow in the case of chemically insulated thermometer has the form of

$$l_p = c p^{-1.5} u_\infty \quad (3.1)$$

In this case l_p rises with the increase in u_∞ considerably slower, than in the case of a catalytic wall at constant temperature. Examples of profiles of nonequilibrium share of atoms are given in fig.3. for parameter values of oncoming flow, shown in table 2.

Table 2

1) Curve	2) gas	3) P, atm	4) $u_\infty, \frac{cm}{sec}$	5) T°_∞, K	6) Scale
1	2	3	4	5	6
1	O ₂	0.1	2·10 ⁴	2700°	1:1
2	O ₂	0.1	6·10 ⁴	2700°	1:1
3	O ₂	1	2·10 ⁴	3000°	1:10 ⁻²

All calculations were made on the SIRELA computer.

The author expresses thanks to G.F. Telenin for supervision of the experiment.

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